Fast and slow radioactive beams in study of light nuclei far from stability

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Abstract

Several examples of results of recent experiments performed with the SPIRAL ISOL-type and GANIL high energy radioactive beams on the properties of nuclei far from stability are presented. Future plans of the GANIL/SPIRAL facility related to the SPIRAL II project are shortly discussed.

1 Introduction

The shell structure, well established for nuclei close to the valley of stability, is expected to evolve significantly in the presence of important excess of neutrons or protons. Nuclei in the vicinity of the drip lines exhibit particularly important changes in the intrinsic structure related to the very low binding energy and the strong influence of the continuum.

In order to obtain the most complete information on these effects a use of radioactive beams in a wide range of isospin and energy is necessary. High energy beams produced by in-flight fragmentation and post-accelerated ISOL beams proved to be complementary with respect to their intensity, isotopic purity and optical quality. Both techniques currently in use at the GANIL/SPIRAL facility offer unique possibilities to make experiments with light radioactive beams (A<80) in the energy range from 30 keV/nucleon to about 80 MeV/nucleon.

2 Fragmentation-like radioactive ion beams

2.1 γ-ray spectroscopy in the vicinity of N=16

An in-beam γ-ray spectroscopy technique using fragmentation reactions is successfully used since several years, in particular at GANIL, to study the structure of exotic nuclei [1]. This provides access to excited states of light neutron-rich nuclei which could hardly be obtained by any other method. However, in this method the primary beam intensity has to be reduced to few enA in order to match the maximum counting rate that individual γ-ray detectors can withstand. To overcome this limitation for accessing nuclei close to the drip-line, one can use a fragmentation of secondary neutron-rich beams. In recent experiments at GANIL, a cocktail of secondary beams of, for example, ^{25,26}Ne, ^{27,28}Na, ^{29,30}Mg, of mean rate 105 pps, has been produced by the fragmentation of a high intensity (400 pnA) ^{36}S beam at 77.5 MeV/u onto a carbon target (348 mg/cm^2) located at the SISSI device [2]. These nuclei were selected through the ALPHA spectrometer and driven to a secondary target composed of a plastic scintillator sandwiched by two carbon foils. The plastic scintillator was used for time of flight and energy loss measurements in order to identify on an event by event basis the ions that have induced reactions in the secondary target.

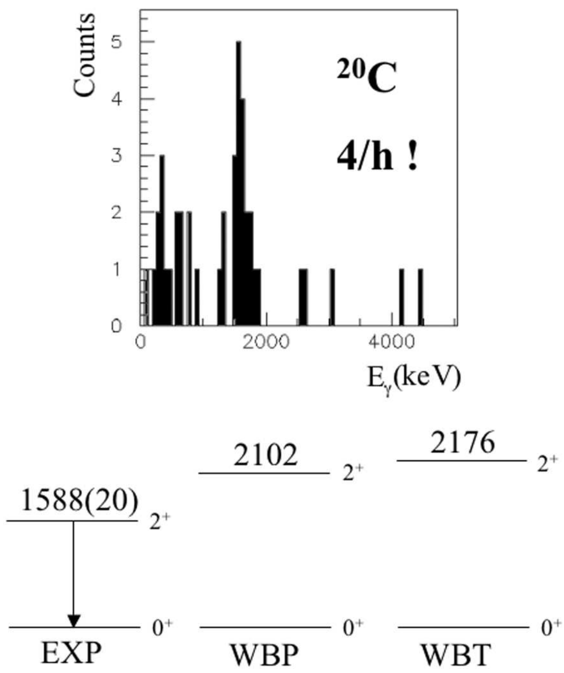

Fig. 1: γ-ray energy spectrum of ^{20}C interpreted as a decay of the 2^+ state.

A gamma array, composed of 74 BaF_2 detectors was surrounding the secondary target in a 4Π geometry, leading to 30% efficiency for an 1.3 MeV γ-ray. γ-rays were collected in coincidence with the tertiary fragments detected in the SPEG magnetic spectrometer. En example of a spectrum obtained from the analysis of γ-ray-fragment coincidences for ^{20}C as well as the deduced and calculated level schemes are presented in Fig. 1. The calculations were performed with the shell model code Oxbash with two different (WBP and WBT) interactions. The experimental spectrum has been obtained with a total of only 189 ^{20}C ions (about 4 ions per hour). The γ-line at 1588(20) keV in ^{20}C was unambiguously assigned to the 2+ to 0+ transition.This result extends the systematics of the 2+ excitation energy up to N=14 in the carbon isotopic chain. The 2+ energy of the ^{22}O isotone is about a factor of two higher than that of ^{20}C.

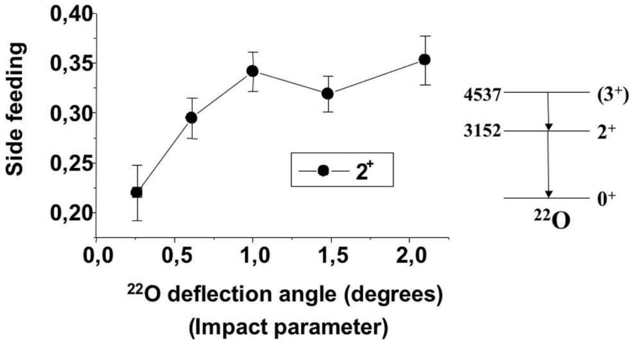

Fig. 2: Feeding of the 2^+ excited state in ^{22}O as a function of the fragment deflection angle.

The double-step fragmentation method allows also to study nuclear reactions involving the radioactive projectile. For example, one may follow a transfer of angular momentum as a function of the fragment deflection angle, which for peripheral reactions might be related to the impact parameter. In Fig. 2 a side feeding of the 2+ state is shown for the ^{22}O fragments produced by the ^{25}Ne projectile (removal of 2 protons and 1 neutron). The 2+ feeding increases as a function of the deflection angle and reaches its maximum at the most central collisions above the grazing angle [4].

2.2 Isomeric beams

Properties of isomeric states in nuclei far from stability give usually the very first information on the evolution of shell structure and nuclear mean field at large isospin values. A very important feature of the search for short-lived isomers with fragmentation reactions is that in a single experiment one may cover a broad range of nuclei, thus mapping general trends in nuclear structure, in particular, in the vicinity of neutron or proton magic numbers as Z=28, N=40 and N=50 [5, 7, 8, 9].

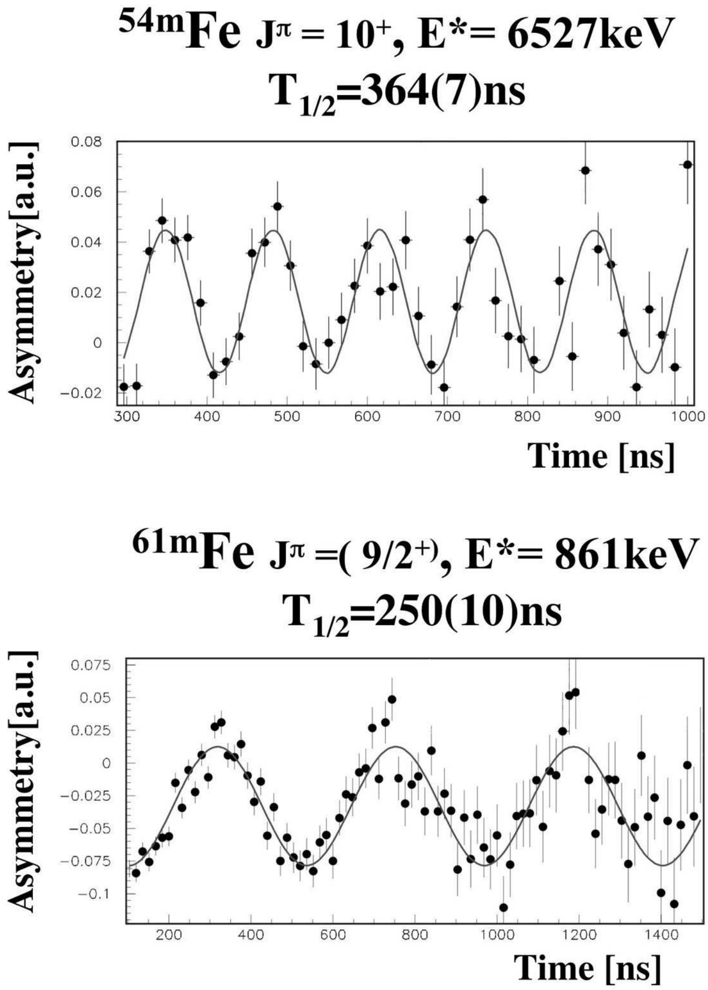

Fig. 3: g-factor measurements for μs-isomers in ^{54}Fe and ^{61}Fe. On-line results are shown.

So far inaccessible regions of the chart of nuclei are explored by means of this technique in order to search for new phenomena at the border of nuclear stability. In order to extract even more detailed information on the isomeric states and on the underlying nuclear structure very recent experiments are dedicated to g-factor and sub-nanosecond lifetimes measurements [4] as well as to the conversion electron spectroscopy [6]. Also a use of aligned and/or polarized isomeric beams at intermediate and relativistic energies seems to be one of the very promising spectroscopic tools in the near future. The first measurement of the g-factors using the Time Dependent Perturbed Angular Distribution method for isomers in the region of ^{68}Ni was published recently by Georgiev et al. [10] (see also contributions of G. Neyens in these proceedings). In a recent experiment at GANIL, the improved experimental technique allowed to measure the g-factors of the short-lived isomeric states in ^{54}Fe and ^{61}Fe (Fig. 3). The extracted g-factor of ^{54m}Fe is in a very good agreement with the literature value. The g-factor of ^{61m}Fe was measured for the first time in this experiment.

In general, the study of short-lived isomers seems to be one of the most fruitful research program at present and, hopefully, at new/upgraded intermediate and relativistic energy facilities (GANIL, GSI, NSCL MSU, RIA, RIKEN etc.), specially in view of the use of very efficient 4Π γ-arrays (EXOGAM, VEGA, NSCL array etc.).

3 ISOL-type radioactive ion beams

The successful experimental program of study of nuclei far from stability going on since about 15 years at GANIL using radioactive beams produced in-flight was extended towards new possibilities offered by high-quality, low energy radioactive beams available at the SPIRAL facility. A construction of SPIRAL was accomplished in 2001 and detailed tests performed with stable and radioactive beams have shown an excellent overall acceleration efficiency of the accelerating system (from the exit of the ion source to the secondary target) ranging from about 20 to 40%. In the beginning of the operation SPIRAL was be able to deliver radioactive beams of noble gases (He, Ne, Ar and Kr) with an intensity of 10^5- 10^8 particles per second in the energy range from about 3 to 25 AMeV. The first experiments were dedicated to measurements of the excited stated of ^{19}Na with the resonant elastic scattering method [3], to an elastic end inelastic scattering of ^{8}He as well as to an in-beam γ-ray spectroscopy experiments with low energy ^{8}He and ^{76,74}Kr beams.

4 Intense beams of fission fragments : SPIRAL II

It is planned that in few years from now a relatively limited range of ions produced by the SPIRAL facility will be extended to the heavier neutron-rich nuclei produced in a low energy fission of uranium in the proposed SPIRAL II facility [11].

A layout of SPIRAL II is presented in figure 4. A new superconducting linear driver (LINAG) will deliver a high intensity, 40 MeV deuteron beam as well as a variety of heavy-ion beams with mass over charge ratio equals to 3 and energy up to 14.5 AMeV.

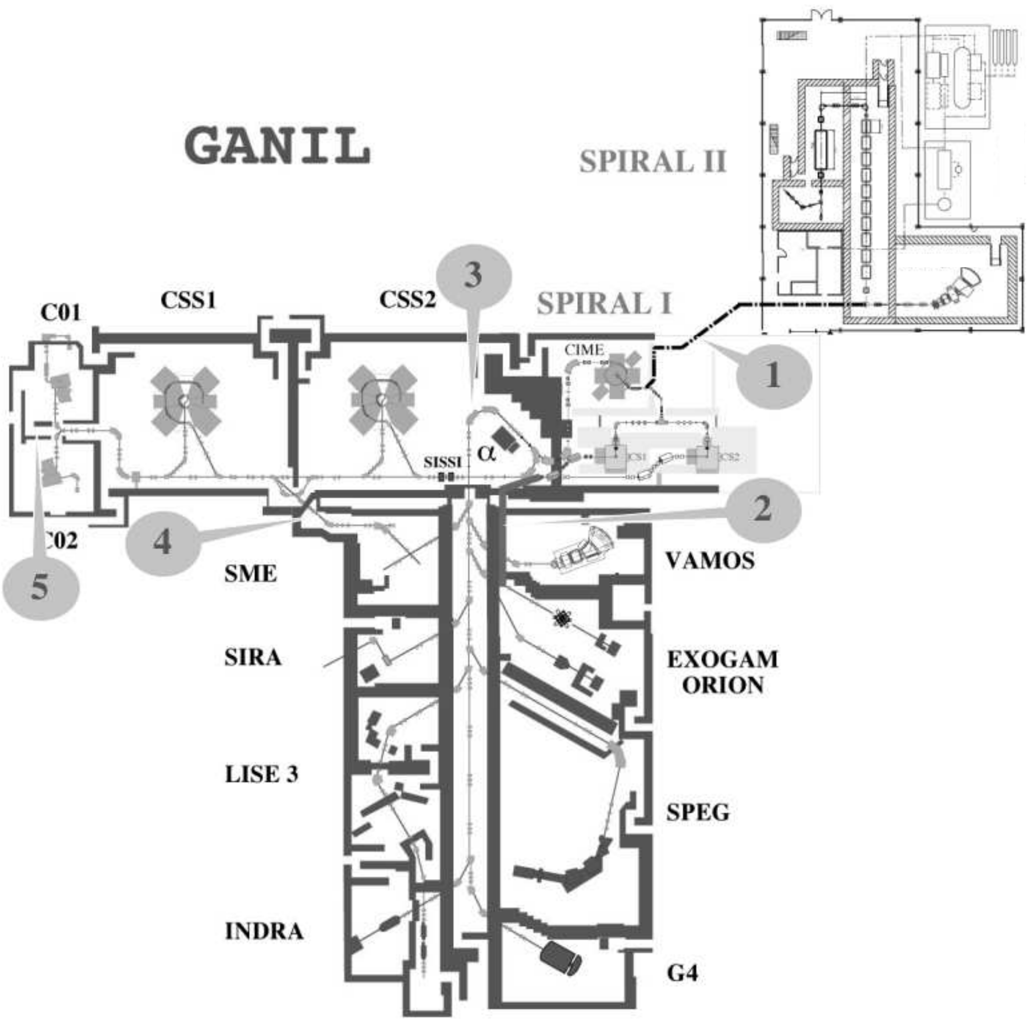

Fig. 4: Schematic view of the GANIL/SPIRAL and proposed SPIRAL II facility.

Using a carbon converter and the 5 mA deuteron beam, a neutron-induced fission rate is expected be 1.3 x 10^{13} fissions/s with a low density UC_x target, and up 5.3 x 10^{13} fissions/s for high-density UC_x. The expected intensities of RNBs after acceleration should reach, for example, 10^9 pps for ^{132}Sn and 10^{10} pps for ^{92}Kr. Besides the method which uses a carbon converter, a direct irradiation of the UC_x with beams of d, ^{3,4}He, ^{6,7}Li, or ^{12}C can be applied if a higher excitation energy leads to higher production rate for a nucleus of interest. The neutron-rich fission products could be complemented by nuclei near the proton drip line provided by fusion-evaporation reactions. For example, a production of up to 8 x 10^4 atoms of ^{80}Zr per second using a 200 μA ^{24}Mg^{8+} beam on a ^{58}Ni target should be possible. The extracted RNBs will be subsequently accelerated to energies of up to 7 AMeV in the existing CIME cyclotron.

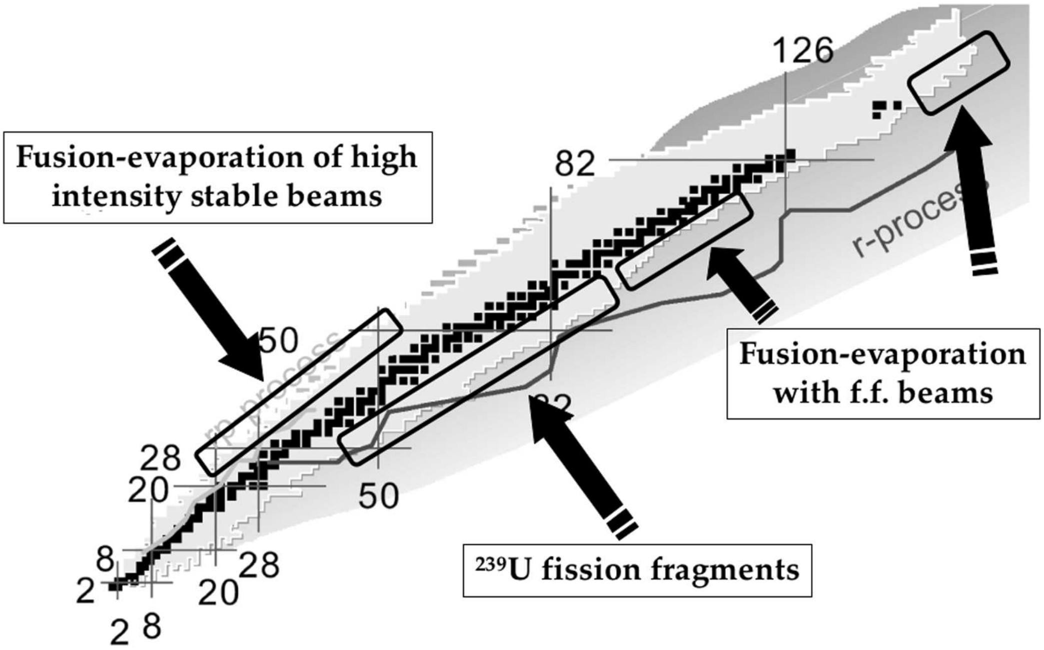

Fig. 5: Regions of exotic nuclei produced with the SPIRAL II beams.

One of the important feature of the future GANIL/SPIRAL/SPIRAL II facility will be a possibility to deliver up to five stable or radioactive beams simultaneously. For example, let's assume that using the LINAG accelerator and the adequate uranium target one produces high intensity radioactive beams of fission fragments. After ionization a beam of the given mass A_1 can be used in the very low energy experimental area (Point 1 in Fig. 4). At the same time mass separator will deliver another beam of mass A_2 for the further acceleration in the CIME cyclotron (Point 2). This beam, thanks to the dedicated beam line from CIME to the G1 and G2 caves, can be used for experiments with EXOGAM and VAMOS. Simultaneously, the standard GANIL's beams can be accelerated and used in the IRRSUD facility (stable beam at about 1 AMeV, Point 4), at the SME beam line (stable beam at 8-10 AMeV, Point 5) and in the existing experimental area (50-100 AMeV stable or radioactive beam produced in-flight, Point 3).

A full description of the nuclear physics topics and interdisciplinary applications which might be covered with the SPIRAL II beams is beyond the scope of this contribution, but one can mention that both high-intensity stable and fission-fragments radioactive beams can be used to cover very broad range of nuclei very far from stability (Fig. 5).

5 Conclusions

The GANIL facility offers unique possibilities to study nuclei far from stability using both fragmentation-like (A<100, E<100 AMeV) and ISOL/SPIRAL RNBs (A<80, E<25 AMeV). Experiments performed recently with these beams, employing the large variety of spectrometers and high efficiency devices like EXOGAM, VAMOS, LISE, SPEG and MUST have shown many spectacular results in the study of nuclear structure. Middle range plans of GANIL are based on the new RNB facility called SPIRAL II which should deliver in several years from now both high intensity ISOL beams of fission fragments and high intensity heavy-ion beams (E<14.5 AMeV, I_{beam} = 1 pmA). Up to 5 stable/radioactive beams in the several tens of keV to 100 AMeV energy range will be delivered simultaneously for experiments on nuclear physics and interdisciplinary research. SPIRAL II might become in the future an integral part of the EURISOL facility.

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